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PRELIMINARY PLANNING FOR NEAR'S LOW-ALTITUDE OPERATIONS AT 433 EROS

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NASA's Near Earth Asteroid Rendezvous (NEAR) spacecraft will be placed into orbit around asteroid 433 Eros on Valentine's Day in the year 2000. The spacecraft will orbit Eros with increasingly lower altitudes as the one year orbit phase progresses. This paper will provide preliminary plans for mission design and navigation during the last two weeks of the orbit phase, where several close passes to the surface will be incorporated to enhance the science return. The culmination of these close passes will result in the eventual landing of the spacecraft on the surface of Eros. The possibility of hovering within 1 km from Eros's surface exists and could be incorporated into the landing design. These close flybys and landing designs will incorporate the preliminary navigation information obtained during NEAR's recent flyby of Eros on December 23, 1998.

INTRODUCTION

On February 14, 2000, an orbit insertion burn will place NASA's Discovery-class Near Earth Asteroid Rendezvous (NEAR) spacecraft (S/C) into orbit around the S-Type asteroid 433 Eros. NEAR will initially orbit Eros with distances ranging from 500 to 100 km in order to characterize the shape, gravity and spin of Eros. Once the physical parameters of Eros are determined reasonably well, the plan is to establish an orbit of the NEAR S/C with increasingly lower altitudes as the one year orbital mission progresses while further characterizing the properties of Eros. Towards the end of the NEAR mission, the scientific interest of obtaining very close observations (< 10 km) can be realized. The navigation during this phase relies on a combination of NASA's Deep Space Network (DSN) radio metric tracking, laser ranging (LIDAR) data from

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the S/C to the surface of Eros, and onboard optical imaging of landmarks on Eros. This paper will provide preliminary plans for mission design and navigation during the last two weeks of the orbit phase, where several close passes to the surface will be incorporated to enhance the science return. The culmination of these close passes will result in the eventual landing of the S/C on the surface of Eros. Several considerations for these plans are given by Antreasian *et al.* [1998]. The objective for the end of the mission will be to land the S/C autonomously using the surface relative information obtained from the onboard LIDAR instrument. The S/C was not designed for landing, but if the S/C impact speed can be kept under 7 m/s, it is believed that the S/C could remain operational for a short period after impact with the asteroid surface. The goal will be to collect and downlink science observations before the S/C loses functionality. The S/C impact speed can be controlled to less than 7 m/s with the use of an onboard LIDAR landing algorithm as discussed by Antreasian *et al.* [1998]. The body-fixed hovering control technique discussed by Scheeres [1999] could greatly enhance the science observations by removing the asteroid-relative motion of the S/C during the landing phase. A stability control analysis of Eros based on the recent flyby information has been performed to locate hovering/landing regions requiring only altitudinal control.

Orbit Dynamics about an Asteroid at Close Range

As described by Scheeres *et al.* [1995], the orbital dynamics of S/C close to a distended body such as Eros are subject to strong perturbations from the gravity field, the major contribution coming from the 2nd degree and order gravity field, which can be reduced to the two terms C_{20} (oblateness) and C_{22} (ellipticity). At close altitudes, the strong perturbations from the irregular gravity field of Eros cause large changes to the S/C orbit characteristics. These effects can lead to unstable situations where the S/C is suddenly placed on either an escape or impact trajectory. While oblateness causes secular changes in the longitude of the ascending node, the argument of periapsis, and mean anomaly, it does not cause orbit instability. The ellipticity effect, however, can cause severe S/C orbit instabilities by directly altering the energy and angular momentum during each orbit. These changes in energy effect the orbit semimajor axis, while changes in angular momentum rate and direction effect eccentricity and inclination. By defining an averaged potential for the ellipticity effect from the gravity harmonic, C_{22}, on the S/C orbit, Scheeres *et al.* [1998] derives the basic form of equations for the changes in energy and angular momentum during one orbit. With the consideration of the variation of these parameters for orbit design, two feasible approaches have been analyzed by Antreasian *et al.* [1998] to effect low altitude flybys of the Eros surface, enabling high-resolution imagery and localized gravitational measurements. These include: (1) tight retrograde orbits which have the drawback of high relative velocity with the surface, and (2) targeted low passes to some latitude and longitude which have the possibility of smaller relative velocity with the surface.

The close passes described above will culminate with a landing of NEAR on the surface of Eros which will mark the end of the mission. The navigation challenge is to be able to execute the final maneuver as late as possible, as this will minimize the impact speed. The measurements available to the S/C during this time are its a priori solution prior to the de-orbit maneuver, the ACS which maintains the S/C attitude during the entire trajectory, and the accelerometers which are used to control the pre-planned maneuvers. To push the impact speed to an appreciably lower value, such as under 1 m/s, requires the inclusion of altimetry data into the navigation design. The simplest approach would have the S/C make altimetry measurements using the LIDAR after the initial descent has commenced. The S/C would compare these measurements to the nominal descent profile and use the offset between them to shift the execution time of all subsequent maneuvers. The implementation of this autonomous control would consist of comparing altitude measurements and their measurement epochs with the nominal profile and shifting the final time by the corresponding amount.

Pointing constraints peculiar to the NEAR S/C for solar array point, science pointing and telecommunications and tracking will be addressed in the paper. Requirements for telecom and tracking during the low passes and landing will be developed.

Eros Flyby on December 23, 1998

A recent aborted rendezvous maneuver upon approach to Eros caused a delay in the original Eros orbital phase of NEAR's mission that was described by Miller *et al.* [1998]. Instead of achieving the necessary

Eros relative velocity which was required for orbit insertion, NEAR continued to fly within 3828 km past the asteroid on December 23, 1998. A large maneuver (932 m/s) was then executed on January 3rd, 1999 to reduce the asteroid relative velocity and return it back for a rendezvous with Eros in February of 2000. Despite the year delay to the main objective of NEAR's mission, the recent flyby of Eros provided important preliminary navigational information for the orbit phase. Preliminary estimates for the physical parameters of Eros, such as shape, mass, spin axis and rotation rate have been determined [Miller *et al.* 1999][Yeomans *et al.* 1999]. The effects of these parameters will be incorporated into the design of the close flyby and landing trajectories. The images of Eros that were obtained during the flyby show interesting features on the surface of Eros. The feasibility of observing this and other features at close range will be discussed.

Close approach images covering over 2/3 of Eros's surface reveal the asteroid's triaxial dimensions to be approximately 33 x 13 x 13 km [Veverka *et al.* 1999]. Though it wasn't significantly above the noise, a apparent gravitational shift in the 2-way X-band Doppler signature was observed during NEAR's close approach [Yeomans *et al.* 1999]. Upon the determination of NEAR's orbit during this flyby using the Doppler, 2-way range and landmark tracking of observed surface features in the images, Eros's gravitational parameter (μ) was estimated to be [Miller *et al.* 1999][Yeomans *et al.* 1999]:

$$\mu = 4.8 \pm 1.2 \times 10^{-4} \text{km}^3/\text{s}^2 \quad (1)$$

Eros's rotational pole position was also determined from this solution to be pointing $15.6° \pm 3.7°$ in Right Ascension and $16.4° \pm 1.8°$ in Declination. A shape model determined from the close approach images has been computed by P.C. Thomas of Cornell University. This model has been slightly modified by Miller *et al.* [1999] and tesselated into an 8200 plate model for use in navigation planning. Assuming constant density, an *a priori* 16 x 16 spherical harmonic gravity model has been inferred from this shape by Miller *et al.* [1999]. The oblateness (C_{20}) and ellipticity (C_{22}) terms derived from this field are:

$$r_o^2 C_{20} = -12.079 \text{ km}^2 \quad (2)$$

$$r_o^2 C_{22} = 20.669 \text{ km}^2 \quad (3)$$

MISSION CONSTRAINTS

Eros-Sun-Earth Geometry

Figure 1 shows the locations of Eros and Earth during the close flyby/landing phase in a North ecliptic view. Also noted in this figure are the positions of Eros and Earth during the time of Eros orbit insertion (EOI) which marks the beginning of the orbit phase. The distances of Eros to the Sun and Earth are approximately 1.5 and 2.1 A.U., respectively at the start of the close flyby/landing phase. The latitude of the Sun and Earth relative to Eros's equator are given in Figure 2. As shown in Figure 2, the direction of the Sun from Eros is nearly aligned with the South pole of Eros (latitude ¡ -80°). Figure 3 displays the Sun-Eros-Earth angle during orbit phase and end of mission. Towards the end of the mission, the Earth is approximately 25° from the Sun direction vector. The implications of these geometries on the design for the close flyby and landing trajectories are discussed below.

Orbit Constraints

A description of the NEAR S/C subsystems and the onboard instruments is given by Santo [1996]. Two-way non-coherent X-Band Doppler and range tracking data are transponded over either NEAR's High Gain Antenna (HGA) or fan-beam antenna. The HGA requires Earth pointing and is used mainly for the transmission of science telemetry. The 40° wedged radiation pattern of the fan-beam antenna allows the S/C to remain in Earth contact during most of the close flyby/landing phase. Science instruments point out the side of the S/C bus 90°to the solar array normal vector, so in order to obtain observations at non-terminator locations the S/C's attitude must be adjusted. Because of the fixed mounting of the science instruments, solar array and high gain antenna, the NEAR mission must operate under several constraints

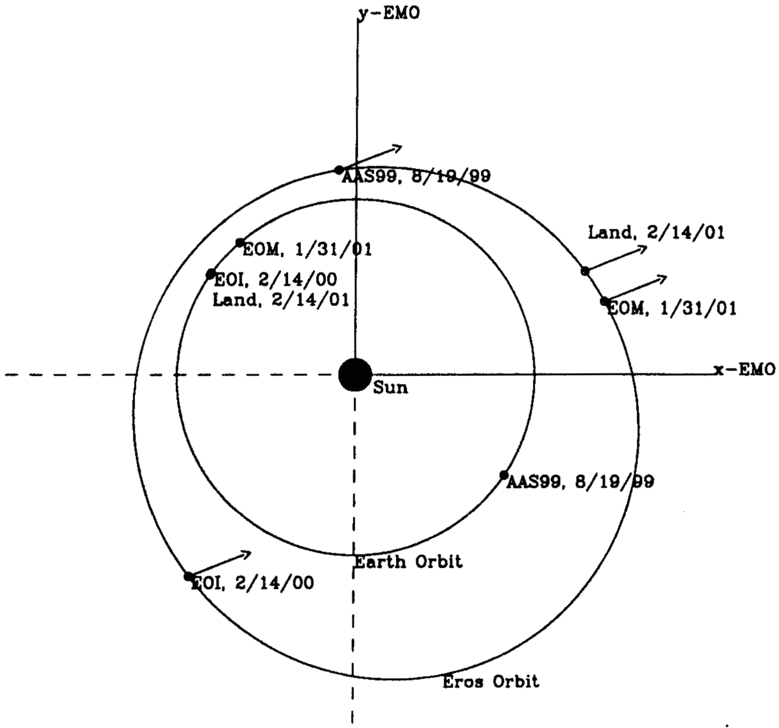

Figure 1: North ecliptic view of Earth and Eros orbits showing significant events. The direction of Eros's pole is indicated by the arrow.

during the orbit phase to ensure the health and safety of the spacecraft while providing near continuous coverage for valuable science[8]. To ensure adequate illumination of the solar arrays for power, the S/C attitude during the orbit phase must be such that the normal of the solar arrays remains within 30° of the Sun direction. At the time of the close flyby/landing phase, however, the Sun-Eros distance allows the solar arrays to maintain adequate power margin with off-sun pointing attitudes up to 46°. Because of this and the additional constraint that the science instruments must always point to nadir, the orbit plane must be oriented such that the orbit normal remain within 46 degrees of the Sun. Tracking also imposes a constraint that the orbit normal remain within 30 degrees of the Earth direction to ensure navigation data and science return. By controlling the S/C orbit inclination, radius and longitude of ascending node, these mission constraints can be met[9]. In addition, so that the S/C never loses power, the S/C is constrained never to fly into the shadow of Eros.

Orbit Stability

Orbit stability should also be considered as imposing constraints on mission design for low altitude passes. These constraints include:

- No direct orbits ($i < 90°$) within 50 km of Eros
- No polar orbits within 50 km of Eros unless specifically verified first (depending on the precise Eros parameters there may be destabilizing resonances from 50 km on down).
- All nominal close orbits will be retrograde, initially within 10° of the equator perhaps higher following additional Eros parameter characterization.

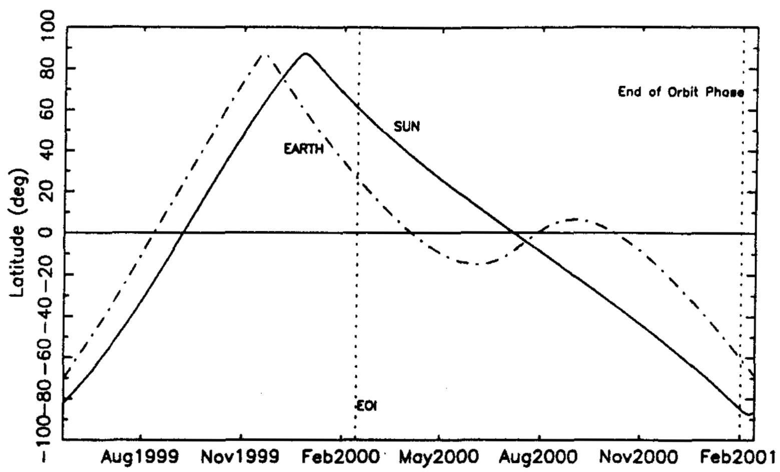

Figure 2: The latitude of the Sun and Earth relative to Eros's equator during the orbit and close flyby/landing phases.

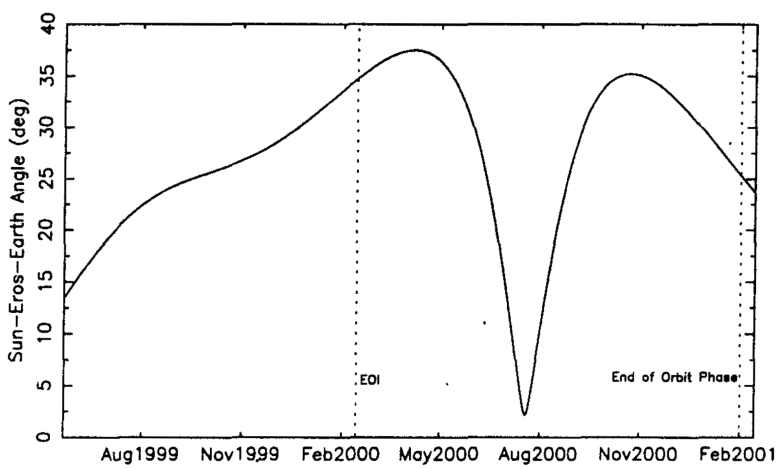

Figure 3: The Sun-Eros-Earth angle during the orbit and close flyby/landing phases.

Tracking Requirements

During critical periods of the orbit phase, such as initial orbit characterization for lower altitude orbits, continuous X-Band Doppler coverage will be required from the DSN's 34 m and 70 m antennas. During the entire orbit phase, landmark tracking images will be acquired at the rate of 8 images per day. Continuous Doppler coverage of propulsive maneuver events will be required from 2 days prior to 1 day after. In addition, two landmark images taken immediately before and two after maneuver execution will be required. Currently, there's no navigational requirement for LIDAR coverage, but its use will complement the radio metric data for determining NEAR's orbit and the physical parameters of Eros. Because of the criticality of the low pass orbits, and landing scenarios that will be described below, it is assumed for this study that continuous Doppler tracking will be provided.

Maneuver Design

Orbit correction maneuvers (OCMs) will be required from time to time to maintain the orbit constraints or to target the trajectory for science purposes. A number of steps in ground operations are performed before an OCM executes, such as maneuver design, implementation, sequence generation, verification and uplink.

During the orbit phase, the time allowed to perform these steps is approximately one week for preparation before OCM execution. During the close flyby/landing phase, this process will have to be condensed to 1 - 2 days. If a maneuver fails to execute, and/or the S/C's orbit becomes unstable such that it may eventually impact or escape, it will be necessary to execute a maneuver as quickly as possible. Under such circumstances, the minimum time required to redetermine the S/C's orbit, and uplink a new maneuver sequence is set at approximately three hours.

Although a significant amount of hydrazine fuel was expended during the aborted rendezvous maneuver anomaly, because of the lower determined mass of Eros [Miller *et al.* 1999] and the redesign of the orbit phase [Helfrich et al. 1999], it is expected that as much as 38 kg fuel will be available for the close flyby/landing phase. The actual amount of propellant margin at the end of the orbit phase will ultimately determine what can be accomplished in this phase. It may be decided to enact the landing phase if it is found that sometime during the orbit phase the fuel level drops to a predetermined limit.

Gravity Modeling at Close Range

Successful close flybys of Eros's surface are dependent upon the correct evaluation of the gravitational acceleration upon the spacecraft at close range. Because of the asteroid's irregular shape, it is known that the spherical harmonic representation of the gravity potential is deficient at locations closer than the largest triaxial dimension. These deficiencies might be due to truncation errors that grow close to the model's radius of convergence or the possibility of the divergence of the harmonic expansion series inside a circumscribing sphere of the largest triaxial dimension[Werner & Scheeres, 1997]. Care must be given when numerically integrating the spacecraft orbit within these regions as the spherical harmonic gravity model could lead to erroneous results. To alleviate these problems, a polyhedron gravity model developed by Werner & Scheeres [1997] has been incorporated into the integration of the trajectory through the close regions, however the partial derivative derivations of the gravity potential with respect to the S/C state and dynamic parameters necessary for orbit determination haven't been completed as yet. The polyhedral gravity for Eros is based on the recently determined shape model and assumes a constant density. One possible trajectory designed for landing may be a free-fall at the southern pole of Eros from a 35 km radial distance. Figure 4 compares the free-fall velocity based on a 16 x 16 spherical harmonic field to the polyhedron gravity model with 8200 plates as a function of radius from 35.4 km. As shown in Figure 4, the spherical harmonic model begins to diverge at the 15 km radial distance. Since the polyhedron gravity model is computationally more intensive, a transition from the spherical harmonic model to the polyhedron model is performed when the spacecraft's radial distance moves inside 20 km. Though the polyhedron model gives an exact solution up to the surface of the asteroid for a given shape and density, it is dependent on the asteroid shape determination and constant density assumption.

Another approach for gravity modeling at close range as discussed by Miller *et al.* [1999], can be performed by representing the asteroid with as many as 12 spherical harmonic gravity fields. This technique may have advantages over the current polyhedron model since it is not dependent upon the constant density assumption and the partial derivatives already exist.

Close Flyby Orbit Design

Orbit Phase

As a result of the delay to NEAR's mission at Eros, Helfrich *et al.* [1999] have redesigned the strategy of the Eros orbit phase using the preliminary parameters described above. After orbit insertion the S/C will orbit the asteroid at distances ranging from 99 to 500 km for the first two months. For simplicity and to satisfy mission constraints described below, the plane of the orbits lie nearly in the Sun Plane-of-Sky. Towards the end of April 2000, NEAR will enter a 51 km near circular orbit for up to 3 months. During this period, the spherical harmonic gravity field should be characterized up to degree and order 8 [Miller *et al.* [1995]. Then NEAR will enter a 100 km near circular orbit and eventually perform a "zero phase" overflight of the subsolar point on Eros's surface. After a month in a 200 km circular orbit, the S/C will maneuver closer to Eros and finally end the last month of the orbit phase (December 31, 2000 - January 31, 2001) in a 35

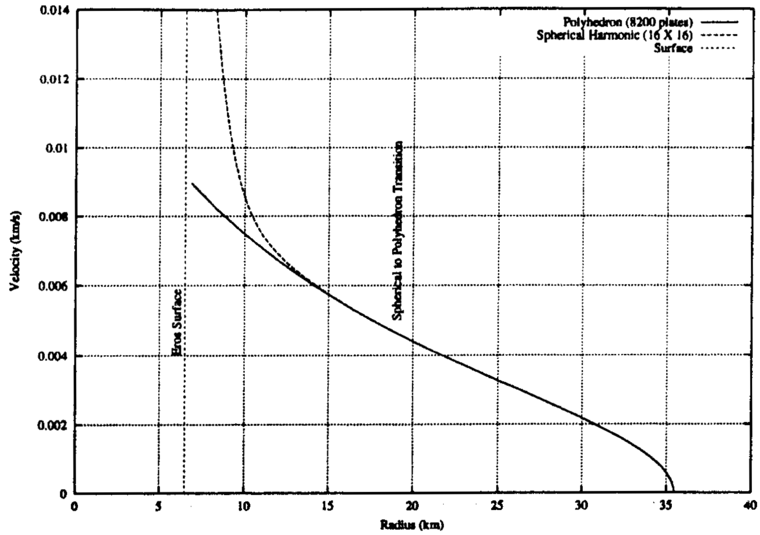

Figure 4: Comparing the S/C's integrated free-fall velocity from a radial distance of 35.4 km for the polyhedron and spherical harmonic gravity potential models.

x 33 km orbit. After this time, the close flyby/landing phase will begin. The end of the NEAR mission will occur after landing on February 14, 2001. The closest approach to the surface of Eros during the orbit phase will occur in the 35 x 33 km orbits (with an inclination, i, of 179° to Eros equator) at altitudes down to approximately 15 km.

Close Flyby Phase

To initiate the close flyby/landing phase, a small ΔV executed at apoapsis of the 35 x 33 km orbit will place the S/C into a 35 x 23 km orbit ($i = 179°$) which has the possibility of achieving altitudes as close as 5 km at the ends of Eros (0° and 180° longitudes). Because the gravitational perturbations greatly perturb the Keplerian osculating orbital elements, the periapsis location and periodicity of the orbit is not easily determined, thus close flybys of the asteroid ends will not always coincide with a periapsis passage although the orbit's period is approximately equal to 2.5 asteroid revolutions. Although resonant orbits maybe great for science purposes, it should be cautioned that resonant orbits may have destabilizing effects. Given the gravitational and physical parameters described above, the orbit appears to be stable for several days. Once the physical parameters of Eros are well determined during the orbit phase, it will be necessary to reevaluate these orbits to ensure they do not suffer from destabilizing effects. Figure 6 shows the altitude variation for this orbit.

After several orbital revolutions a transfer orbit will will eventually place the spacecraft into a 50 x 50 km orbit ($i = 179°$). From this orbit a close flyby trajectory will then be enacted. Because the apoapsis is raised following a flyby of the trailing edge of the asteroid, a close flyby with periapsis at longitudes in the 2nd ($90° < \lambda < 135°$ and 4th quadrant ($270° < \lambda < 360°$) are preferred for S/C safety.

The close flyby orbit is inclined at 143° to the equator of Eros. The minimum altitude occurs 11.7 minutes before the closest approach (defined by the minimum orbital radius) with an altitude of 0.97 km over a latitude/longitude of -33 and -32 degrees respectively. The initial orbit has apoapsis radius at 58.5 km and has (actual) periapsis radius at 16 km. After the flyby the apoapsis radius is increased to 111 km, giving us plenty of time to regain control of the S/C. At periapsis radius the orbit has an altitude of 5 km. Figure 5 shows this trajectory in the Sun-Plane-of-sky coordinate frame. In this figure, the asteroid rotates in the right-hand sense (clockwise) while NEAR orbits in the counter-clockwise (retrograde) direction. Figure 7 shows the ellipticity effects on the S/C orbit after periapsis. The apoapsis radius is raised to 100 km.

Table 1: Close Flyby and Landing Timeline

Date (ET)	Segment	Orbit (km x km)	Period (Hrs)	i (Deg)	i_{sps} (Deg)	Length (Days)	Comments
12/31/00 12:30	17	35 x 33	16	179	174	38	End of Orbit Phase
2/1/01 04:41	18	35 x 23	13	179	174.6	2.3	Close flybys of 0°and 180°longitudes
2/3/01 10:50	19	35 x 50	23	179	174.6	1.4	Transfer to 50 km orbit
2/4/01 20:30	20	51 x 50	28	179	174.6	2.7	Close flyby staging orbit
2/7/01 13:09	21	51 x 16	16(20)	145(141)	148(143)	0.3	Close flyby of lat, long = -33°, -32°

Landing/Hovering Scenario

Requirements and Capabilities

For the NEAR spacecraft to enact a controlled landing on Eros a number of different capabilities are needed. First, the spacecraft trajectory must be targeted accurately enough to the initial descent state so that the landing control system only needs to control the descent rate and not the landing footprint on the Eros surface. Second, during the descent the spacecraft must be able to orient itself so as to match its attitude with the Eros attitude, meaning that the spacecraft must slowly turn itself in inertial space as the asteroid rotates beneath it. Due to the fast rotation rate of Eros the neglect of this effect could cause considerable trouble at the end of the landing phase. Third, the S/C must be able to control its descent as it falls to the surface.

The control loop design can be quite simple, using the LIDAR returns to estimate altitude and altitude rate with a fixed number of discrete maneuvers to be executed at preassigned altitudes, with the magnitudes of the burns parameterized by a lookup table relating altitude rate to desired ΔV magnitude. The direction of the burns will nominally be along the local surface normal, which the S/C will be oriented along due to its capability to match the asteroid rotation in open loop. Ideally we wish the touchdown on the surface to be as slow as possible, but there are a variety of design constraints that hamper us in this, e.g., LIDAR operating range, ΔV errors, position and velocity uncertainties, gravity uncertainties, and rotation rate uncertainties to name a few.

During descent the spacecraft will only have altitude information – its lateral motion will be unsensed in real time since the optical navigation camera will not be used in the closed loop control. Images will be taken for replay later (if the S/C does not complete the landing) and can be used to reconstruct the spacecraft motion very accurately. Since the spacecraft will not have lateral control a question of interest is what the footprint of the spacecraft will be on the surface. Since the NEAR spacecraft has not been designed to have any capability after touchdown, the precise region where it hits the surface is not of great concern. However, if instead of allowing the craft to touch down on the surface, we control it to a constant altitude above the asteroid surface then the lateral motion of the spacecraft becomes of greater interest.

If the spacecraft can maintain a controlled descent to the surface of Eros then it also has the capability to hover over the surface as well. To switch from one control scheme to the other can be enacted by changing the control law so that the spacecraft exerts a given amount of ΔV every time it's sensed altitude drops beneath some characteristic height. Due to the relatively weak gravitational pull of Eros the control effort needed to enact such a control is well within the capabilities of the spacecraft. Hovering over the asteroid for an extended period of time would enable a series of detailed high resolution images of the asteroid surface as well as an opportunity to gain high resolution returns on the X-ray and γ-ray instruments.

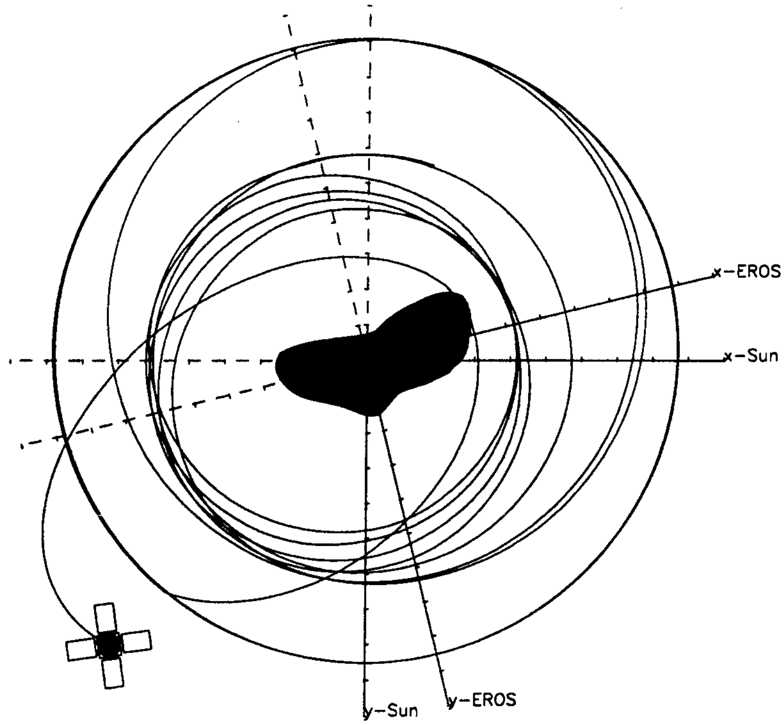

Figure 5: The close-flyby orbits shown in the Sun Plane-of-sky frame.

Stability of Hovering Spacecraft

If the spacecraft is to hover for a certain amount of time above the Eros surface, its lateral stability becomes of interest. The simplest way to characterize the stability of the spacecraft trajectory as it lands or hovers is to treat the spacecraft hovering position as a fixed point - an equilibrium point - in the asteroid-fixed frame and investigate the linear stability of a slightly perturbed trajectory about this point. Although the actual control law does not hover by implementing a constant thrust, this serves as a convenient model with which to study the stability of hovering motion.

For an asteroid with a uniform rotation rate Ω and a gravitational force potential of U, the total thrust vector required to hover at a given position vector $\mathbf{r}$ in the body-fixed frame is:

$$\mathbf{T} = -\frac{\partial U}{\partial \mathbf{r}} + \Omega^2 \hat{\mathbf{z}} \times (\hat{\mathbf{z}} \times \mathbf{r}) \tag{4}$$

where $\hat{\mathbf{z}}$ is the rotation pole of the asteroid. If the spacecraft applies this thrust and continues to rotate itself in inertial space then it will effectively be hovering over the asteroid at the position vector $\mathbf{r}$.

The stability of such an "artificial" trajectory was studied in Scheeres [1999]. The stability of the forced equilibrium point can be computed using the Eros force model and evaluated for its implications for the NEAR spacecraft. We have done this at an altitude of 100 meters above the surface of Eros using the flyby model [Veverka *et al.* 1999]. Shown in Figure 9 is the stability type of the hovering point 100 meters above the surface of Eros as a function of longitude and latitude. The stability "Types" are defined in the caption. In Figure 10 the characteristic time of the instability for the hovering point is shown. When there is more than one exponential root we take the minimum associated characteristic time, as this characterizes the speed with which the hovering spacecraft will drift away from its control point. In general an initial error will increase by an order of magnitude within $e \sim 2.718\ldots$ charateristic times. From this we see that hovering over the Eros surface should be feasible over limited time spans.

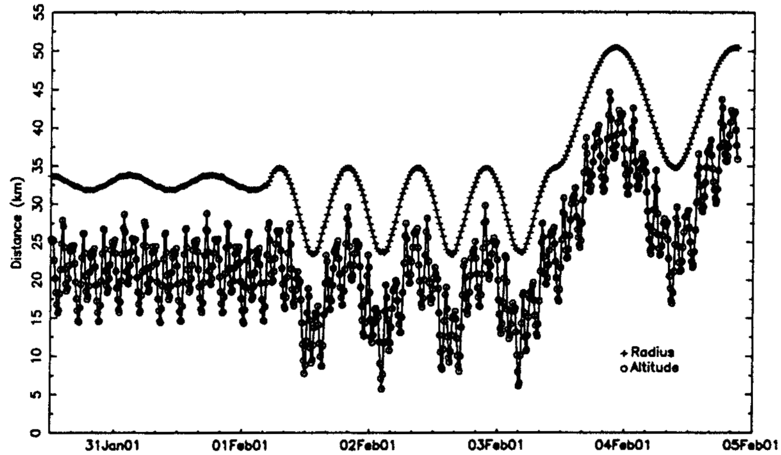

Figure 6: The radial and altitudinal distances at the end of the orbit phase, through the 35 x 25 km orbits and at the transfer to the 50 km orbits.

Test Simulation of NEAR hovering

To better evaluate the system we simulated the simple hovering control at various positions over the Eros surface. The control law was implemented without errors so the natural dynamics in this system could be studied more efficiently. For the control law we assumed that the spacecraft held a given attitude in the Eros-fixed space, implemented by continually commanding the spacecraft to rotate in inertial space at the same rate as the asteroid. Next the spacecraft was placed close to the surface and given an initial velocity to match, locally, the velocity of the asteroid surface. Then the spacecraft is allowed to drop towards the surface, continually measuring the distance from its current location to the surface point that lies along its nominal orientation vector – fixed in the Eros-fixed space. Whenever the altitude along this direction drops below some fixed control value the spacecraft enacts a maneuver to reverse its fall rate – applying a ΔV twice the fall rate in the opposite direction of the fall rate. This ensures that the spacecraft will have some "breathing room" between maneuvers.

As a result of the simulations we found that it was feasible to hover over certain portions of the asteroid surface, but that there was no immediate way to identify those areas which were safest. The dynamics of the spacecraft – once the altitude control is turned on – can become quite complex and involves the local stability properties of the hovering position, the topology of the asteroid (as this affects how the control system will operate) and the placement of the hovering position in the asteroid frame. Figure 11 shows the cost associated with hovering over Eros with the altitude control set at 100 meters above the surface. Since in order to hover, the spacecraft will need to hover continuously, the ΔV rates ($cm/s/min$) are displayed.

Shown in Figure 12 are several different trajectories of a hovering NEAR spacecraft over Eros, computed as above. We note that some of them wander over the entire asteroid, but that others of them stay confined to a relatively small area.

The key for initiating the hovering orbit phase is to maintain as high of accuracy as possible leading up to the insertion into the nominal hovering phase. To do this, its best to perform the insertion with a minimum number of maneuvers, while trying to reduce the transit time to the insertion point. The best way to do this would be to start out in a circular orbit at a "safe" radius, getting the orbit into the same plane as the injection point will lie at (once the S/C gets to that point). Then perform one targeted maneuver that will place the S/C on an elliptical orbit that will fly over the desired radius at the desired time. This is analogous to the close flyby orbit described above. Note that this point is not necessarily the periapsis of the orbit. Once there, the S/C performs one maneuver to null out its body-relative velocity – perhaps giving itself a small bias velocity in the "up" direction to avoid a situation where the S/C immediately starts to fall. Since everything will have been planned out in advance, the S/C knows what attitude it should have and can fire up the LIDAR to commence the closed-loop control. The initial de-orbit maneuver should cost

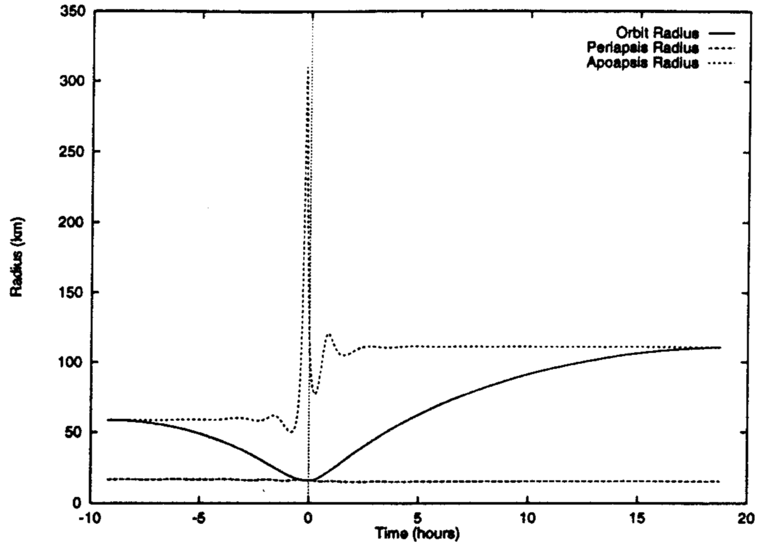

Figure 7: The change in apoapsis radius, etc after the trailing edge close flyby orbit (inclination = 143°).

around 1 m/s, and the final maneuver to "kill" the body-relative velocity will be on the order of 7 m/s, assuming a similar orbit to our low-altitude flyby.

CONCLUSIONS

A few preliminary plans for obtaining unprecedented close science observations of Eros at the end of NEAR's mission have been presented. The plan is to acquire observations at altitudes less than 10 km. The closest observations in NEAR's orbit phase are at altitudes of approximately 15 km during the 35 x 33 km orbits. The close flyby/landing phase will begin where the orbit phase left off by entering a tight retrograde orbit (35 x 23 km) to acquire close observations at altitudes as low as 5 km of the long ends (longitudes = 0°, 180°) of the asteroid. The S/C will then transfer into a 50 km circular staging orbit where a close flyby at a distance of approximately 1 km from Eros's surface will be attempted. Analysis of this type of orbit reveals that the closest approach to the asteroid surface does not always coincide with the periapsis location. By designing this type of orbit to closely flyby the trailing edge of the asteroid which will subsequently raise the apoapsis distance, a margin of safety is added to the time to redetermine the S/C's orbit following the flyby. Another type of close flyby strategy is planned whereby the S/C's orbital velocity is canceled near the South pole of Eros and the S/C enters a free-fall. At an altitude less than 1 km as sensed by the LIDAR instrument, the S/C executes an escape maneuver. To end the mission, the S/C will again be placed into a free-fall near the South Pole, this time a simple autonomous landing algorithm will be enacted which executes maneuvers based on the LIDAR measurements and a nominal descent profile. In addition a landing design has been discussed that considers hovering the S/C at an altitude of 100 m for a few moments before landing. A stability control analysis of body-fixed hovering at this altitude around the surface of Eros has been performed. A simulation of a simple hovering control law indicates that a stable region exists at an equatorial location close to 135°longitude. To ensure adequate power margin, navigational tracking and instrument coverage of Eros and science return, these orbit designs have considered the geometries of the Earth, Sun, Eros and its rotational pole upon mission constraints that the fixed mounting of NEAR's instruments, solar arrays and tracking antennas have imposed.

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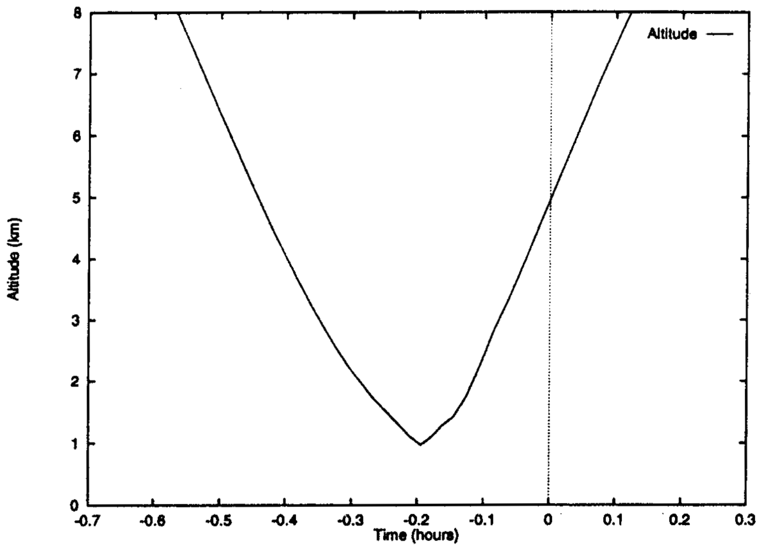

Figure 8: The altitude of the s/c during the close flyby orbit.

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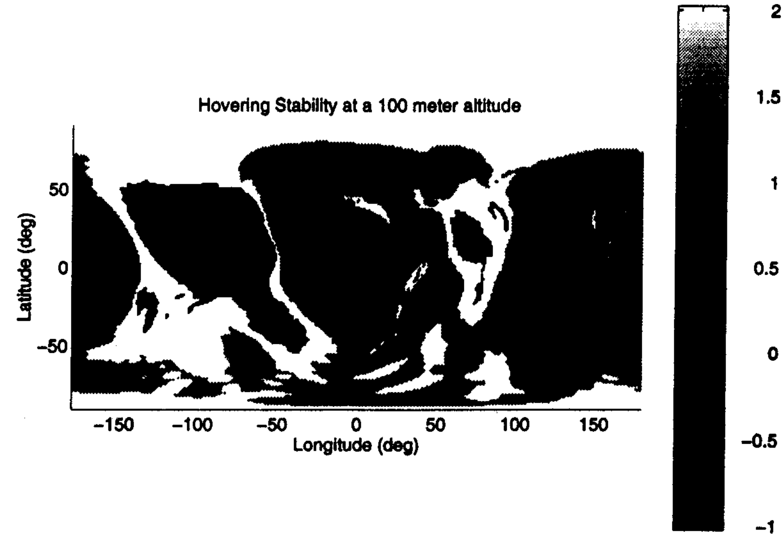

Figure 9: Stability Type as a function of latitude and longitude at an altitude of 100 meters over the surface of Eros. Type -1 has one complex mode (four roots) that consists of stable and unstable manifolds each filling a two-dimensional plane, with an additional stable mode filling a two-dimensional plane. Type 0 has three stable modes, each filling a two-dimensional plane. Type 1 has two stable modes and one hyperbolic mode that consists of one stable and one unstable root each lying on a one-dimensional manifold. Type 2 has one stable mode and two hyperbolic modes. The "type" of stability over the asteroid surface has implications for how a hovering spacecraft will drift over time.

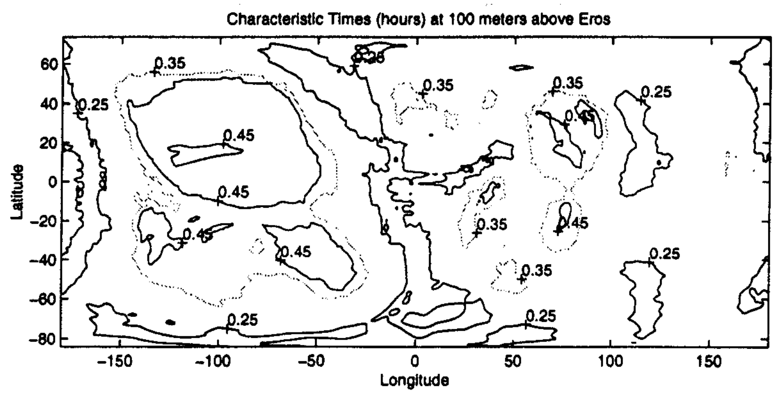

Figure 10: Minimum characteristic time of unstable motion over the surface of Eros (at a 100 meter altitude) This plot gives an indication of the speed with which the unstable modes will force the spacecraft to deviate from its chosen hovering position.

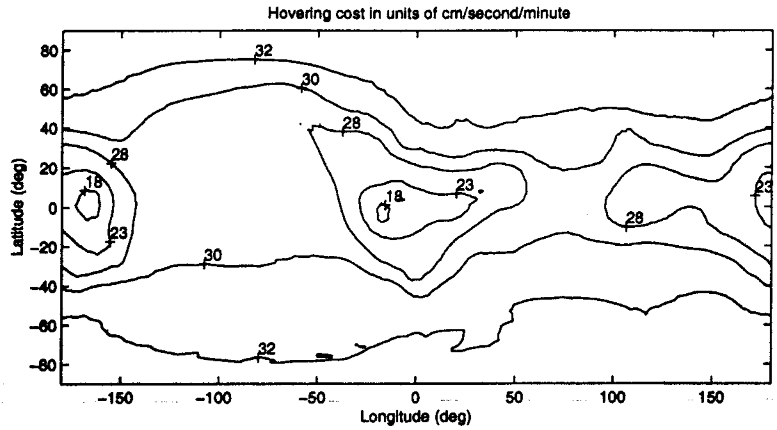

Figure 11: Rate of ΔV cost for hovering 100 meters above Eros at various regions

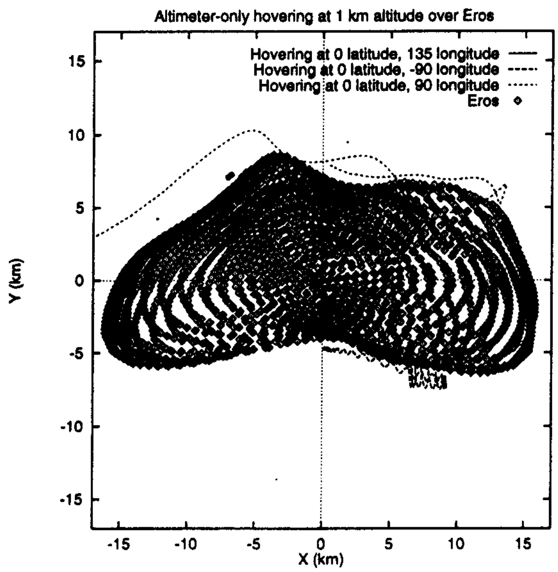

Figure 12: Three different hovering trajectories above Eros. The hovering trajectory at 135° longitude is stably confined to a small region of the surface, the trajectory initially at $-90°$ longitude drifts relatively slowly in longitude, while the trajectory initially at 90° is highly unstable and wanders over a large region of the asteroid surface. The two unstable trajectories can be associated with regions of stability types -1 and 2.